NA61/SHINE: DETECTOR UPGRADES AND PHYSICS PLANS BEYOND 2020*

Pawel Staszel

for the NA61/SHINE Collaboration

Institute of Physics, Jagiellonian University
S. Łojasiewicza 11, 30-348 Kraków, Poland

(Received January 29, 2019)

The measurements of open charm meson production was proposed as an important tool to investigate the properties of hot and dense matter formed in nucleus–nucleus collisions. Recently, the experimental setup of the NA61/SHINE experiment was supplemented with a Vertex Detector which was motivated by the importance and the possibility of the first direct measurements of open charm meson produced in heavy-ion collisions at SPS energies. First test data taken in December 2016 on Pb+Pb collisions at $150A$ GeV/c allowed to validate the general concept of D^0 meson detection via its $D^0 \rightarrow \pi^+ + K^-$ decay channel and delivered a first indication of open charm production. The physics motivation of open charm measurements at SPS energies, pilot results on open charm production and, finally, the future plans of measurements in the NA61/SHINE experiment after LS2 are presented.

DOI:10.5506/APhysPolBSupp.12.465

1. Introduction

The SPS Heavy Ion and Neutrino Experiment (NA61/SHINE) [1] is a fixed-target experiment located at the CERN Super Proton Synchrotron (SPS). The NA61/SHINE detector is optimized to study hadron production in hadron–proton, hadron–nucleus and nucleus–nucleus collisions. The strong interaction research program of NA61/SHINE is dedicated to the study of the properties of the onset of deconfinement and the search for the critical point of strongly interacting matter. These goals are being pursued by investigating $p+p$, $p+A$ and $A+A$ collisions at different beam momenta from $13A$ to $150A$ GeV/c. In 2016, NA61/SHINE was upgraded with the Small Acceptance Vertex Detector (SAVD) based on MIMOSA-

* Presented at the XIII Workshop on Particle Correlations and Femtoscopy, Kraków, Poland, May 22–26, 2018.

26AHR sensors developed in IPHC Strasbourg. Construction of this device was mostly motivated by the importance and the possibility of the first direct measurements of open charm meson production in heavy-ion collisions at the SPS energies. Precise measurements of charm hadron production by NA61/SHINE are expected to be performed in 2021–2024.

2. Physics motivation for open charm measurements

One of the important aspects of relativistic heavy-ion collisions is the mechanism of charm production. Several models were developed to describe charm production. Some of them are based on dynamical and others on statistical approaches. The estimates from these models for the average number of produced c and $\bar{c}$ pairs ($\langle c\bar{c}\rangle$) in central Pb+Pb collisions at $158A$ GeV/c differ by up to a factor of 50 [2, 3] as illustrated in Fig. 1 (left). Therefore, obtaining precise data on $\langle c\bar{c}\rangle$ will allow to distinguish between theoretical predictions and learn about the charm quark and hadron production mechanism. A good estimate of $\langle c\bar{c}\rangle$ can be obtained by measuring the yields of D^0, D^+ and their antiparticles because these mesons carry about 85% of the total produced charm [4].

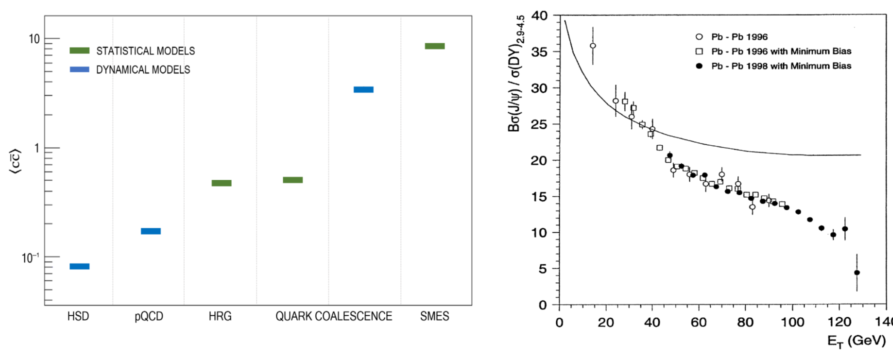

Fig. 1. (Colour on-line) Left: Mean multiplicity of charm quark pairs produced in the full phase space in central Pb+Pb collisions at $158A$ GeV/c calculated with dynamical models (black/blue bars): HSD [5, 6], pQCD-inspired [7, 8], and Dynamical Quark Coalescence [9], as well as statistical models (grey/green bars): HRG [10], Statistical Quark Coalescence [10], and SMES [3]. Right: The ratio of $\sigma_{J/\psi}/\sigma_{\mathrm{DY}}$ as a function of transverse energy (a measure of collision violence or centrality) in Pb+Pb collisions at $158A$ GeV measured by NA50. The curve represents the J/ψ suppression due to the ordinary nuclear absorption [11].

Charm mesons are of special interest in the context of the phase transition between confined hadronic matter and the quark–gluon plasma (QGP). The $c\bar{c}$ pairs produced in the collisions are converted mostly into open charm mesons and, to a lesser extend, into charmonia (J/ψ mesons and its excited states). The production of charm is expected to be different in confined and deconfined matter. This is caused by different properties of charm carriers in these phases. In confined matter, the lightest charm carriers are D mesons, whereas in deconfined matter, the lightest carriers are charm quarks. Production of a $D\bar{D}$ pair ($2m_D = 3.7$ GeV) requires an energy about 1 GeV higher than production of a $c\bar{c}$ pair ($2m_c = 2.6$ GeV). The effective number of degrees of freedom of charm hadrons and charm quarks is similar [12]. Thus, in the statistical approach, more abundant charm production is expected in deconfined than in confined matter. Consequently, in analogy to strangeness production [3, 13], a change of collision energy dependence of $\langle c\bar{c}\rangle$ may be a signal of the onset of deconfinement.

Figure 1 (right) shows results on $\langle J/\psi\rangle$ production normalized to the mean multiplicity of Drell–Yan pairs in Pb+Pb collisions at the top SPS energy obtained by the NA50 Collaboration. The solid line shows a model prediction for normal nuclear absorption of J/ψ in the medium. NA50 observed that J/ψ production is consistent with normal nuclear matter absorption for peripheral collisions but is more suppressed in central collisions. This so-called anomalous suppression was attributed to the J/ψ dissociation effect in the deconfined medium. However, the above result is based on the assumption that $\langle c\bar{c}\rangle \sim \langle \mathrm{DY}\rangle$ which may be incorrect due to several effects, such as shadowing or parton energy loss [14]. Thus, the effect of the medium on $c\bar{c}$ binding can only be quantitatively determined by comparing the ratio of $\langle J/\psi\rangle$ to $\langle c\bar{c}\rangle$ in nucleus–nucleus to that in proton–proton reactions. In Pb+Pb collisions, the onset of color screening should be seen as a decrease of the $\langle J/\psi\rangle$ to $\langle c\bar{c}\rangle$ ratio for more central collisions. This clearly shows the need for large statistics data on $\langle c\bar{c}\rangle$.

3. Performance of SAVD

The SAVD was built using sixteen CMOS MIMOSA-26 sensors [15]. The basic sensor properties are: 18.4×18.4 μm^2 pixels, 115 μs time resolution, 10×20 mm^2 surface, 0.66 MPixel, 50 μm thick. The sensors were glued to eight ALICE ITS ladders [16], which were mounted on two horizontally movable arms and spaced by 5 cm along the z (beam) direction. The detector box was filled with He (to reduce beam–gas interactions) and contained an integrated target holder to avoid unwanted material and multiple Coulomb scattering between target and detector. More details related to the SAVD project can be found in Ref. [17].

The first test of the device was performed in December 2016 during a Pb+Pb test run. The obtained primary vertex resolution along the beam direction of 30 μm was sufficient to perform the search for the D^0 and $\bar{D}^0$ signals. Figure 2 (right) shows the first indication of a D^0 and $\bar{D}^0$ peak obtained from the data collected during the Pb+Pb run in 2016.

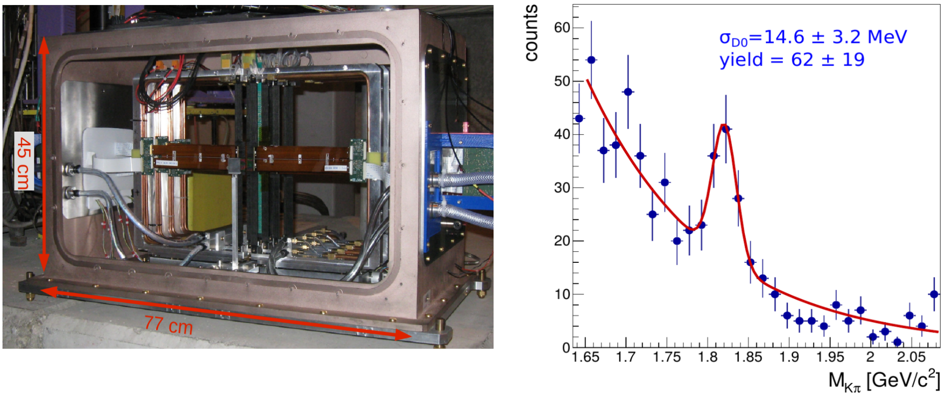

Fig. 2. Left: The SAVD used by NA61/SHINE during the data taking in 2016 and 2017. Right: The invariant mass distribution of D^0 and $\bar{D}^0$ candidates in central Pb+Pb collisions at 150A GeV/c after the background suppression cuts. The particle identification capability of NA61/SHINE was not used at this stage of the analysis [2].

Successful performance of the SAVD in 2016 led to the decision to also use it during the Xe+La data taking in 2017. About 5×10^6 events of central Xe+La collisions at 150A GeV/c were collected in October and November 2017. During these measurements, the thresholds of the MIMOSA-26 sensors were tuned to obtain high hit detection efficiency which led to significant improvement in the primary vertex reconstruction precision, namely the spatial resolution of the primary vertices obtained for Xe+La data is on the level of 1 μm and 15 μm in the transverse and longitudinal coordinates, respectively. The distribution of the longitudinal coordinate ($z_{\rm prim}$) of the primary vertex is shown in Fig. 3 (left) (see Ref. [2] for details). The Xe+La data are currently under analysis and are expected to lead to physics results in the coming months.

The SAVD will also be used during three weeks of Pb+Pb data taking in 2018. About 1×10^7 central collisions should be recorded and 2500 D^0 and $\bar{D}^0$ decays can be expected to be reconstructed in this data set.

4. Proposed measurements after LS2

During the Long Shutdown 2 at CERN (2019–2020), a significant modification of the NA61/SHINE spectrometer is planned. The upgrade is primarily motivated by the charm program which requires a tenfold increase of the data taking rate to about 1 kHz and an increase of the phase-space coverage of the Vertex Detector by a factor of about 2. This, in particular, requires construction of a new Vertex Detector (VD), replacement of the TPC read-out electronics, implementation of new trigger and data acquisition systems and upgrade of the Projectile Spectator Detector. Finally, new ToF detectors are planned to be constructed for particle identification at mid-rapidity. This is mainly motivated by possible future measurements related to the onset of fireball formation. The detector upgrades are discussed in detail in Ref. [2]. The data taking plan related to the open charm measurements forsees measurements of 500M inelastic Pb+Pb collisions at $150A$ GeV/c in 2021 and 2023. This data will provide the mean number of $c\bar{c}$ pairs in central Pb+Pb collisions needed to investigate the mechanism of charm production in this reaction. Moreover, the data will allow to establish the centrality dependence of $\langle c\bar{c}\rangle$ in Pb+Pb collisions at $150A$ GeV/c and thus address the question of how the formation of QGP impacts J/ψ production. Central (0–30%) Pb+Pb collisions at $40A$ GeV/c are planned to be recorded in 2024. This data, together with the result for central Pb+Pb collisions at $150A$ GeV/c, will start a long-term effort to establish the collision energy dependence of $\langle c\bar{c}\rangle$ and address the question of how the onset of deconfinement impacts charm production.

Figure 3 (right) shows simulated distributions of $D^0 + \bar{D}^0$ mesons in rapidity and transverse momentum for all generated particles (black dots) and for particles that passed the acceptance and background reduction cuts (blue squares). The presented plots refer to 500M inelastic Pb+Pb collisions at $150A$ GeV/c. Total uncertainty of $\langle D^0\rangle$ and $\langle\bar{D}^0\rangle$ is expected to be about 10% and is dominated by systematic uncertainty.

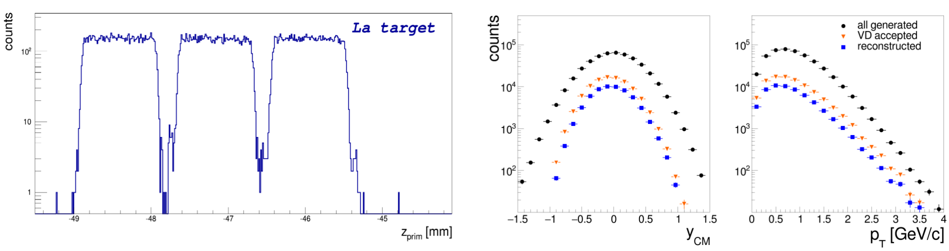

Fig. 3. (Colour on-line) Left: Distribution of longitudinal coordinate of the primary vertex $z_{\rm prim}$ for interactions in the La target, which was composed of three 1 mm plates. Right: Simulation of rapidity (left) and transverse momentum (right) distributions of $D^0 + \bar{D}^0$ mesons produced in about 500M inelastic Pb+Pb collisions at $150A$ GeV/c. Dots indicate all generated mesons, triangles mesons within the VD acceptance and squares mesons within the VD acceptance and passing background suppression cuts.

The NA61/SHINE Collaboration also foresees to continue measurements of hadron production induced by proton and kaon beams for neutrino physics to improve the precision of hadron production measurements for the currently used T2K replica target and to perform measurements for prototypes of T2K-II, Hyper-Kamiokande and DUNE targets.

Recently, new measurements of nuclear fragmentation cross sections for cosmic ray physics have been proposed. The objective of nuclear fragmentation cross-section measurements is to provide high-precision data needed for the interpretation of results from current-generation cosmic ray experiments. Namely, the proposed measurements will allow to extract the characteristics of the diffuse propagation of cosmic rays in the Galaxy. A better understanding of the cosmic-ray propagation is needed to study the origin of Galactic cosmic rays and to evaluate the cosmic-ray background for signatures of astrophysical dark matter (see Ref. [2] for more details).

This work was supported by the National Science Centre, Poland (NCN) grants 2014/15/B/ST2/02537 and 2015/18/M/ST2/00125.

REFERENCES

[1] N. Abgrall *et al.* [NA61/SHINE Collaboration], *JINST* **9**, P06005 (2014).
[2] A. Aduszkiewicz *et al.* [NA61/SHINE Collaboration], CERN-SPSC-2017-038/CERN-SPSC-2018-008/SPSC-P-330-ADD-10.
[3] M. Gaździcki, M.I. Gorenstein, *Acta Phys. Pol. B* **30**, 2705 (1999).
[4] W. Cassing, E.L. Bratkovskaya, *Nucl. Phys. A* **831**, 215 (2009).
[5] O. Linnyk, E.L. Bratkovskaya, W. Cassing, *Int. J. Mod. Phys. E* **17**, 1367 (2008).
[6] T. Song, private cummunication.
[7] R. Gavai *et al.*, *Int. J. Mod. Phys. A* **10**, 2999 (1995).
[8] P. Braun-Munzinger, J. Stachel, *Phys. Lett. B* **490**, 196 (2000).
[9] P. Levai *et al.*, *J. Phys. G* **27**, 703 (2001).
[10] A.P. Kostyuk *et al.*, *Phys. Lett. B* **531**, 195 (2002).
[11] M.C. Abreu *et al.*, *Phys. Lett. B* **477**, 28 (2000).
[12] R.V. Poberezhnyuk, M. Gazdzicki, M.I. Gorenstein, *Acta Phys. Pol. B* **48**, 1461 (2017).
[13] J. Rafelski, B. Müller, *Phys. Rev. Lett.* **48**, 1066 (1982).
[14] H. Satz, *EPJ Web Conf.* **71**, 00118 (2014); *Adv. High Energy Phys.* **2013**, 242918 (2013).
[15] MIMOSA26 User Manual: `http://www.iphc.cnrs.fr/IMG/pdf/M26_UserManual_light.pdf`
[16] B. Abelev *et al.* [ALICE Collaboration], 2013, CERN-LHCC-2013-024/ALICE-TDR-017.
[17] M. Deveaux *et al.*, *EPJ Web Conf.* **171**, 10003 (2018).